Intrinsic Broadening of the Transverse Momentum Spectra in Ultrarelativistic Heavy-Ion Collisions?

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Abstract

The mean transverse momentum in high energy nuclear collisions is studied. The formation of a Color Glass Condensate results in an increase of the square of the mean transverse momentum with the charged multiplicity per unit rapidity and unit transverse area. This prediction is in agreement with the presently available data, in particular with the heavy-ion data, lending support to the notion that the transverse momentum spectra in ultrarelativistic collisions of heavy nuclei might be controlled by intrinsic p_T broadening and not by hadronic rescattering, i.e. transverse flow.

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The initial gluon distribution in high-energy nuclear collisions can be described by the formation of a so called Color Glass Condensate (CGC) [1–3]. The gluon multiplicity per unit rapidity and transverse area has been shown to depend on the initial gluon density which saturates at very high energies [4–8]. This saturation should be observable in the mean transverse momentum spectra which should scale then like the square root of the charged multiplicity per unit rapidity and unit *transverse* area, hence:

$$\langle p_T \rangle^2 \ \sim \ \frac{1}{\pi R^2} \frac{dN_c}{dy} \tag{1}$$

by dimensional arguments. In this paper, we are going to confront this prediction with presently available experimental data. As we will outline in the following, we find that the above relation eq. (1) is fulfilled by both, pp or p$\bar{\text{p}}$ and heavy-ion data. This observation seems to suggest that the transverse momentum broadening seen in elementary and heavy-ion collisions results from the same underlying physics, namely the intrinsically generated p_T broadening in the partonic phase, i.e. from the CGC. This implies that transverse flow from rescattering in heavy-ion collisions in the hadronic phase might be small compared to the transverse push initially generated in the partonic phase.

The study of the particle transverse momentum as a function of multiplicity is interesting as it might reveal features of a phase transition to a quark-gluon plasma [9]. The increase of the mean p_T with the charged multiplicity is a well known experimental fact for high-energy electron and proton-antiproton collisions (see e.g. [10,11] and references therein). Mass identified particle production were measured at the Tevatron for p$\bar{\text{p}}$ collisions at up to $\sqrt{s} = 1.8$ TeV by the E735 collaboration [12,13]. The data is shown in fig. 1. It is apparent from the figure, that the increase of the mean p_T depends on the mass of the hadron and is stronger for heavier particles. We have also plotted the results of two-parameter fits using the scaling law eq. (1) by the solid curves. The two parameters are the coefficient of $\sqrt{dN_c/dy}$ and the value of p_T as the multiplicity shrinks to zero. We note that the agreement with the data is quite reasonable. The mean p_T seems to follow the saturation momentum of the gluon distribution function resulting in a square root dependence with the multiplicity density. The onset of the curve at small mean p_T is due to soft physics. The difference in the slope parameter for pions, kaons, antiprotons will be discussed later.

We have also checked numerically that the more accurate data for all negatively charged particles as measured by the UA1 collaboration is in accord with the scaling law (1). The slope is slightly larger than for the pions in fig. 1 due to the small admixture of negatively charged kaons and antiprotons. The increase of the mean p_T with multiplicity for p$\bar{\text{p}}$ for the different hadrons has been also reproduced by more sophisticated partonic models, like the HIJING model [14], the quark-gluon string model [15], and the dual parton model [16]. Radial flow has been also suggested as a possible explanation [17], but it is at variance with the small source sizes determined from two-pion correlations [18].

Next, we test our model for relativistic (heavy-)ion collisions. Presently published data with the highest available bombarding energy is from the ISR collider at CERN for light ions up to $\alpha\alpha$ collisions [19] An enhancement of the slope of the mean p_T with the multiplicity density is observed. At the same bombarding energy of $\sqrt{s} = 31$ GeV, the increase amounts to about 30% for $\alpha\alpha$ collisions compared to dd collisions, which is about 30% larger than that for pp collisions. According to (1), the increase of the slope of the mean p_T squared
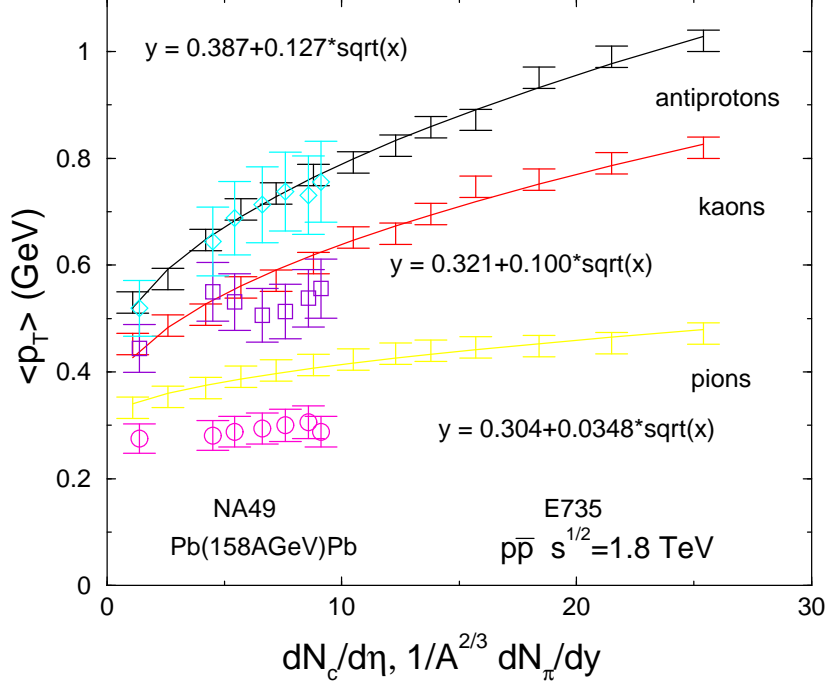
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FIG. 1. The mean p_T as a function of the charged multiplicity per unit rapidity and area. Shown are the data points for p$\bar{\text{p}}$ collisions at $\sqrt{s} = 1.8$ TeV from E735 at the Tevatron as taken from [13], and heavy-ion data for pp and PbPb collisions at 158 AGeV from NA49 at the SPS as extracted from [20]. The solid lines are fits through the Tevatron data using the scaling law of the CGC.

should scale like the unit transverse area, i.e. with $A^{2/3}$. More precisely, it would scale like $r_p^2/(r_0^2 A^{2/3})$ where r_p is the proton radius and $r_0 \approx 1.1$. The mean p_T will increase then by about $2^{1/3}$, i.e. by 26%, when going from pp to dd to $\alpha\alpha$ in excellent agreement with the observation made at ISR [19].

Concerning truly heavy-ion collisions, the first events from Brookhaven's Relativistic Heavy-Ion Collider (RHIC) for AuAu collisions at $\sqrt{s} = 130$ AGeV are presently under investigation [21]. The NA49 experiment at CERN's SPS has published multiplicity and mean p_T distributions as a function of the centrality for PbPb collisions at midrapidity [20]. We extract the charged particle multiplicity per unit rapidity from the pion multiplicity and by setting $dN/dy = 160$ for the most central bin. The charged multiplicity density per unit transverse area is then given by dividing it with $A^{2/3}$ (setting the proton radius to $r_p = 1$ fm would give an additional shift in the scale down by $(r_p/r_0)^2$, i.e. by 20%). Systematic error bars for the mean p_T have not been given in [20]. We adopt an ad hoc value of 10% for the systematic error [22]. The resulting points are plotted in fig. 1. We note that the results for the protons and kaons are then within the error bars on top of the data from the Tevatron and the corresponding fit for a CGC. The results for the mean p_T for the pions are somewhat lower though.

However, this difference is due to the moderate dependence of the mean p_T on the bombarding energy (see [10,13] and references therein). For energies comparable to the SPS the mean transverse momentum averaged over multiplicity $\langle p_T \rangle$ is about 0.33 GeV for pions for p$\bar{\text{p}}$ collisions and increases to 0.38 GeV at $\sqrt{s} = 1.8$ TeV. If the points for the pions from

NA49 are shifted accordingly, they are consistent with our fit to the Tevatron data points. A similar shift for the kaons points does not change the agreement with the scaling curve. The proton points are then slightly higher than our scaling curve fitted to the Tevatron data, but they are consistent with the Tevatron data points within the error bars. The slight energy dependence of $\langle p_T \rangle$ can be explained by a slight increase of the saturation momentum with $\sqrt{s}$. Assuming a power law behavior [23], we find that the energy dependence of $\langle p_T \rangle$ for charged particles as measured by the UA1 collaboration goes like $\sim E^{\delta}$ [10] with $\delta = 0.08$. Note, that a logarithmic dependence is also in accord with the data [10]. The increase with energy is considerably larger for heavier hadrons as seen by the E735 collaboration [13], so that for protons we get $\delta = 0.19$ instead. We remark, that the data seems to indicate that there is an threshold effect, an onset of the increase of the transverse momentum at an energy around $\sqrt{s} = 100 - 200$ GeV which is right in the region accessible at RHIC. The gluon distribution function starts to turn on at $x < 0.01$. This is the region where the rise in p_T should begin. In heavy-ion reactions the start of the rise appears at smaller energies which might be due to the increase of the gluon density in AA collisions compared to pp collisions. The onset of gluon saturation might be visible by studying the mean transverse momentum for pA and light AB systems at the SPS. At a certain size of the colliding system, the $\langle p_T \rangle^2$ dependence should then increase with the multiplicity per unit transverse area. There will be also a moderate enhancement of $\langle p_T \rangle$ compared to pp collisions due to the increase of the saturation momentum Q_s^2 with $A^{1/3}$. The A dependence of the color-glass condensate for pA and light systems has been studied in detail in [24].

In conclusion, there seems to be a dramatic correspondence of the mean p_T appropriately scaled by the transverse unit area for heavy-ion collisions and p$\bar{\text{p}}$ collisions at much larger energies. The origin of this behavior is lying in the saturation of the initial gluon transverse momentum distribution. This observation, if taken seriously, leads to a drastic conclusion: it is possible that the transverse momentum distribution of hadrons in heavy-ion collisions is mainly controlled by the initial momentum distributions of gluons and not by effects from hadronic rescattering. The good agreement between the two curves from p$\bar{\text{p}}$ and heavy-ion collisions for the mean p_T does not leave room for a significant transverse expansion via a collective transverse flow. We note, that a random walk model can also describe the p_T broadening in heavy-ion collisions without transverse flow [25] (see also [26] for a critical discussion).

What we left open is the question why heavier particles have larger mean p_T in p$\bar{\text{p}}$ and in heavy-ion collisions. A possible explanation can be provided by the coalescence model for the formation of hadrons at the confinement phase transition. Of course, the formation of hadrons is an extremely complex process which requires a detailed dynamical approach. With this in mind, let us state the following. Naively, the mean p_T of a hadron will scale with the number of quarks in the coalescence model as the quark momenta are added up to form a hadron. The mean p_T for protons should then be 3/2 times larger than that for pions. The strange quark will take a special role in this picture as the associated production from gluons needs to overcome the mass threshold. After coalescence, many pions will come from subsequent resonance decays, e.g. from the ρ meson. The ρ meson picks up 2 times the intrinsic p_T, but decays to two pions with about half that p_T. Hence, the combination of these effects results in a p_T ratio between 3/2 and 3. The momentum spectra of kaons on the other hand are not affected by this resonance effect and end up with about 2/3 times the

proton mean p_T. Indeed, the mean p_T for protons compared to pions shows an increase by about 1.5–2.0 over a wide range of energy (see e.g. the data compiled in [13]), the kaon mean p_T being between the mean p_T for pions and protons. Also, the slope parameters measured for pions and protons in PbPb collisions has been extracted to be around 190 MeV and 300 MeV [27], respectively, reflecting a similar increase in the mean p_T.

We conclude with a brief comment about a possible test of this picture. The physical quantity which is computed from the Color Glass Condensate is the phase space distribution

$$\frac{1}{\pi R^2} \frac{dN}{dy d^2 p_T} \quad . \tag{2}$$

On dimensional grounds for equal size nuclear collision at some fixed impact parameter

$$\frac{1}{\sigma} \frac{dN}{dy d^2 p_T} = F(Q_s^2/p_T^2) \quad . \tag{3}$$

In this equation, Q_s^2 is the saturation momentum squared which characterizes the Color Glass Condensate at the impact parameter for the collision. An attempt to extract this saturation momentum has been done by Kharzeev and Nardi [8]. The cross section σ is that for a collision to occur at the impact parameter at hand. This formula predicts that the p_T distributions at different impact parameters can be rescaled into one another. If true, it is a remarkable verification of the approximate scale-invariance of the Color Glass Condensate.

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